

# Impact of Aggregation Level on the Performance of Dynamic Lightpath Adaptation under Time-Varying Traffic

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**Abstract**—In this article we focus on lightpath adaptation under time-varying traffic in a dynamic elastic optical network (EON) implementing flexgrid optical technology. In the considered scenario, a number of IP/MPLS metro area networks performing traffic aggregation are connected through a core EON. We explore the elastic spectrum allocation (SA) capability of EON and, in this context, we study the effectiveness of three alternative SA policies, namely *Fixed*, *Semi-Elastic* and *Elastic*. For each elastic SA policy, we develop a dedicated algorithm which is responsible for adaptation of spectrum allocated to lightpath connections in response to traffic changes. The evaluation is performed for a set of network scenarios, each one characterized by a different level of traffic aggregation, and hence different traffic variability. As simulation results show, the effectiveness of SA policies highly depends on both the aggregation level and maximum lightpath capacity. In particular, in our experiments up to 21% more traffic is served with the proposed elastic SA than with the fixed SA in a network with low aggregation and high lightpath capacity.

**Key words**—dynamic lightpath adaptation, elastic optical network, IP/MPLS network, time-varying traffic.

## I. INTRODUCTION

The advent of the flexible spectrum grid (*flexgrid*) technology [1], [2] brings new opportunities to next-generation transport networks since it allows for elastic, adaptive, highly-scalable, and on-demand bandwidth (bit-rate) provisioning in optical networks. The key technologies that are paving the way to devise these novel elastic optical network (EON) architectures are: 1) the availability of flexgrid ready Wavelength Selective Switches (WSS) to build Bandwidth-Variation Optical Cross-Connects (BV-OXC), 2) the development of advanced modulation formats and techniques, both single-carrier (such as k-PSK, k-QAM) and multi-carrier (such as O-OFDM), to increase efficiency and being capable of extending the reach of optical signals avoiding expensive electronic regeneration (3R); 3) Multi-Flow Transponders (MF-TP) that are able to deal with several flows in parallel, thus adding even more flexibility and reducing costs [3]. BV-OXCs allow creating an optical routing path (*lightpath*) through the network by switching transmitted signals within their frequency bandwidth to appropriate switch output ports. Concurrently, the role of MF-TP is to adapt the client data to be sent to/received from the optical network using just enough frequency resources. ITU-T has recently

revised the G.694.1 recommendation and included the definition of a flexible wavelength division multiplexing (WDM) grid [4]. According to [4], an optical *channel* has flexibly (ad-hoc) assigned spectrum that covers both the frequency range occupied by the optical signal and the guard band required for the roll-off filters. For more details on EON architectures and proof-of-concept EON experiments we refer to [2], [5], [6].

Recently, in [7] and [8] we have investigated how traffic aggregation can be done, in part, at the optical layer, so that to reduce the IP/MPLS network size. In the considered single-layer network approach, IP/MPLS routers that aggregate traffic from metro area networks (hereinafter referred to as *aggregation networks*) are equipped with MF-TPs and are connected to BV-OXCs of a flexgrid-based core network. The core network provides connectivity between aggregation networks (see Fig. 1). In [8] we show that if the core network is extended towards the edges and, by these means, the number of metro areas is increased, then significant Capital Expenditure (CAPEX) savings (of above 20-30%) can be obtained. However, having a larger number of relatively small metro areas implies a reduction in the traffic aggregation at the IP/MPLS layer, thus resulting in higher variability of the data rate of traffic flows offered to the optical layer along the day.

One of the main advantages of EON is the capability to allocate spectrum resources elastically, according to traffic demands. Indeed, the resources may be utilized efficiently, firstly, because of the higher granularity of the flexgrid which allows matching closely the allocated spectrum and the signal bandwidth, secondly, due to the elastic (adaptive) spectrum allocation (SA) in response to traffic variations. On the contrary to WDM networks, in which the width of optical channels is fixed and equal, in EON the channel allocated to a lightpath may be expanded/reduced when the required bit rate of a demand increases/decreases. In this context, adaptive SA with a known a priori 24-hour traffic patterns has been addressed in [9]-[11] and spectrum adaptation under dynamic traffic demands was studied in [12]-[13]. Concurrently, different policies for elastic SA were proposed, including symmetric [9]-[11] and asymmetric [9], [10], [13] spectrum expansion/reduction around a reference frequency as well as the entire spectrum re-allocation policy [9]-[10].

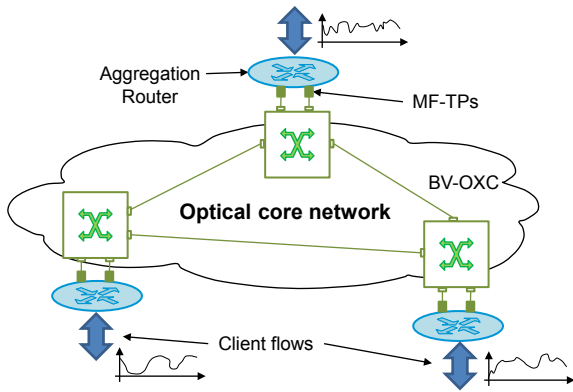


Fig. 1. A flexgrid-based optical core network connecting aggregation IP/MPLS networks.

First in [9] and later in [10] we have shown that in EON with time-varying traffic and under a priori known (deterministic) traffic demands, elastic SA policies implementing lightpath adaptation (either symmetric, asymmetric, or reallocation-based) allow the network to serve more traffic than a fixed SA policy. In this paper, we extend the work to a dynamic network scenario. Our main objective is to assess the efficiency of elastic SA policies for networks with different levels of traffic aggregation and, consequently, with different traffic variability. In particular, we investigate the relation between aggregation and the performance of the proposed elastic SA policies. To this end, we evaluate the performance of elastic SA assuming different dimensions of the flexgrid-based core network, which in turn translates into the level of aggregation of the traffic to be carried by lightpaths in the core network [7]-[8]. As a result of extending the core network towards the edges, there may exist the problem of lightpath reachability, especially for the lightpaths with large capacity (e.g. 400Gb/s) [14]; this can be solved by managing the modulation format and introducing inverse-multiplexing (e.g. 4x100 Gb/s). To the best of our knowledge, the impact of aggregation level and traffic variability on the efficiency of adaptive spectrum allocation under time-varying traffic has been not studied so far in a dynamic EON scenario. Note that this is one of the issues that should be investigated in order to recognize true benefits of the flexgrid technology and its ability to be a successor of current fixed-grid technologies in optical transport networks.

The remainder of the paper is organized as follows. In Section 2, we define the problem of dynamic lightpath adaptation, present the considered spectrum allocation policies, and describe dedicated lightpath adaptation algorithms. In Section 3, we perform simulation experiments and study the performance of the proposed SA policies. We consider three realistic network topologies, each of different dimension, and analyze two different scenarios in which the capacity of the lightpaths is limited to either 400Gb/s or 100Gb/s. Finally, in Section 4 we conclude the work.

## II. DYNAMIC LIGHTPATH ADAPTATION

In this Section, we address the problem of lightpath adaptation in EON under time-varying traffic demands. First,

we discuss the assumption that we take in our study and we describe the considered spectrum allocation policies. Then we formulate the problem of lightpath adaptation and, for each SA policy, we propose an algorithm to solve it.

We focus on an EON which implements a discrete frequency grid defined in [4]. In particular, a flexgrid consists of a set of nominal *central frequencies* (CF) and a set of frequency *slices*, where a slice corresponds to a spectrum segment that lays between two CFs. Flexgrid [4] requires to have the spectrum allocated symmetrically around a CF and, therefore, each lightpath occupies an even number of slices. In [4], nominally, the CF granularity, i.e., the spacing between neighboring CFs, and the slice width is equal to  $\Delta_f=6.25\text{GHz}$ . However, we notice that finer granulates, such as  $\Delta_f=3.125\text{GHz}$ , may be more advantageous, as shown in [8].

In our study, we assume that the profile of the client flows arriving to the aggregation router is known. A traffic profile is characterized by a guaranteed bit-rate and a range of variation, given for a considered set of time periods. Therefore, lightpaths can be pre-planned, using for example the models in [10], and established on the network. We assume that the lightpath capacity is limited and, therefore, several lightpath connections may exist between a pair of aggregation networks. Note that the optical signal reach may be increased by using such techniques as inverse-multiplexing without a need for excessive 3R regeneration. Once in operation, the established lightpaths must elastically adapt their capacity so as to convey as much bit-rate as possible from the demanded by the aggregation networks. Any significant change in traffic that entails a change in the amount of optical spectrum of a lightpath (i.e., spectrum expansion/reduction) results in a request which is sent to the control plane of the flexgrid core network to find the appropriate SA for that lightpath (see problem definition in Sec. II.B). In response to this request, a dynamic SA algorithm (see Sec. II.C) which is implemented in a Path Computation Element (PCE) is in charge of adapting the spectrum allocation in accordance to the SA policy which is used in the network (see Sec. II.A).

### A. Spectrum Allocation Policies

In [10] we have discerned three alternative spectrum allocation policies for time-varying traffic demands (Fig. 2).

The SA policies put the following restrictions on the assigned CF and the allocated spectrum width, in particular:

1. *Fixed* (Fig. 2a): both the assigned CF and spectrum width do not change in time. At each time period, demands may utilize either whole or only a fraction of the allocated spectrum to convey the bit-rate requested for that period.
2. *Semi-Elastic* (Fig. 2b): the assigned CF is fixed but the allocated spectrum may vary. Here, spectrum increments/decrements are achieved by allocating/releasing frequency slices symmetrically, i.e., at each end of the already allocated spectrum while keeping invariant the CF. The frequency slices can be shared between neighboring demands, but used by, at most, one demand in a time interval.



side of the allocated spectrum (line 9). Finally, the returned value ( $f_p$ )' is obtained by computing the new CF value so as to minimize the shifting of CF (line 11).

### III. RESULTS

In this Section, we present and discuss the performance results of a dynamic EON connecting aggregation networks and operating with elastic spectrum allocation policies under time-varying traffic demands.

#### A. Scenario

We consider three scenarios representing different levels of traffic aggregation consisting in three different core networks: TEL21, TEL60, and TEL100, with 21, 60, and 100 nodes, respectively. These networks are based on the Telefónica (TEL) network presented in Fig. 3. The main characteristics of the networks are presented in Table III.

For the sake of fairness in further comparisons, each core network is designed to provide approximately the same blocking performance at a given total traffic load. To this aim, the models and methods proposed in [16] to design core networks under dynamic traffic assumption are adapted and used to fit our pre-planning needs. Note that, although the relation between traffic load and un-served bandwidth is kept pretty similar in all defined scenarios, the number of core nodes strongly affects the level of traffic aggregation. Namely, since the analyzed core networks cover the same geographical area and the offered traffic is the same for each network, the lower number of core nodes the larger aggregation networks as well as the higher the flow grooming on lightpaths.

In the network planning phase, the flows between core nodes are generated with a uniform distribution and following the time-variant bandwidth distribution used in [9]. In particular, three different traffic profiles (TP), defined by their  $h^{min}$  and  $h^{max}$  bit-rate values, are used to compute bit-rate fluctuations of traffic flows in time. Here, a granularity of 1h is considered. Each flow belongs to one of those TPs (with the same probability) and bit-rate fluctuations are randomly chosen following a uniform distribution within an interval defined by  $h^{min}$  and  $h^{max}$ . The considered TPs with their bandwidth intervals are TP1 = [10,100], TP2 = [40,200], and TP3 = [100,400]. We assume that all traffic flows between a pair of core nodes are transported using a minimum number of lightpaths. Furthermore, for the completeness of our study, the lightpaths' maximum capacity is limited either to 100 Gb/s or to 400 Gb/s. The quadrature phase shift keying (QPSK) modulation format is assumed.

Having the above defined core network topologies and traffic demands, a network planning problem is solved using the algorithms proposed in [10] for each of the considered SA policies. The problem concerns finding initial lightpaths between each pair of core nodes with the objective to maximize the amount of served bit-rate. The obtained solutions of the network planning phase, i.e., the routing and the initial spectrum allocations of established lightpaths, are used as input data for our elastic network simulator.

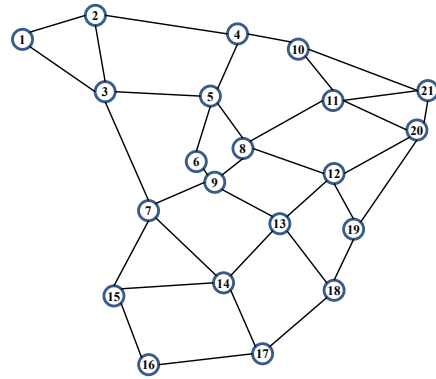


Fig. 3. TEL21 network topology used in this paper.

TABLE III DETAILS OF NETWORK TOPOLOGIES

	Nodes	Links	Nodal degree
TEL21	21	35	3.33
TEL60	60	90	3.0
TEL100	100	125	2.5

In order to evaluate the algorithms presented in Sec. II, we have developed an ad-hoc event-driven simulator in OMNET++ [17]. Similarly as for the planning phase, a set of flows following the TPs defined above is set up. For each flow, the requested bit-rate varies randomly ten times per hour, i.e. a finer, with respect to the network planning phase, and randomly-generated granularity both in time and bit-rate is considered in the simulator. Hence, bit-rate variations arrive randomly to the system and a grooming module at the aggregation router ensures that the offered bit-rate can be served. In particular, if either more spectrum resources are needed for a lightpath or these resources can be released, the grooming module requests the core network to perform an elastic operation on that lightpath. To this end, algorithms in Table I and Table II are executed provided that either the *Semi-Elastic* or the *Elastic* policies are used. Eventually, the lightpath adaptation is not performed whenever the *Fixed* policy is applied.

In our experiments, the optical spectrum width is set to 1.2 THz and the slice width is fixed and equal to 3.125GHz (spectral granularity of 6.25GHz).

#### B. Efficiency of SA policies

Firstly, we analyze the efficiency of SA policies in the considered core network scenarios assuming different lightpath capacity limits (100 Gb/s and 400 Gb/s). We recall that for the largest core network (i.e., TEL100) we have the lowest level of traffic aggregation and, as a consequence, the highest variability of traffic offered to the core network.

Fig. 4 illustrates the accumulated percentage of un-served bit-rate (UB) as a function of the offered traffic load, represented by the average load for each core network, and lightpath capacity limit. We observe that when the aggregation level is high (TEL21) and lightpath capacity is limited to 100 Gb/s, all the SA policies offer similar performance. It can be explained by the fact that since the traffic variability is low in this scenario, the network does not benefit from adaptive SA. Furthermore, since the volume of aggregated traffic is large

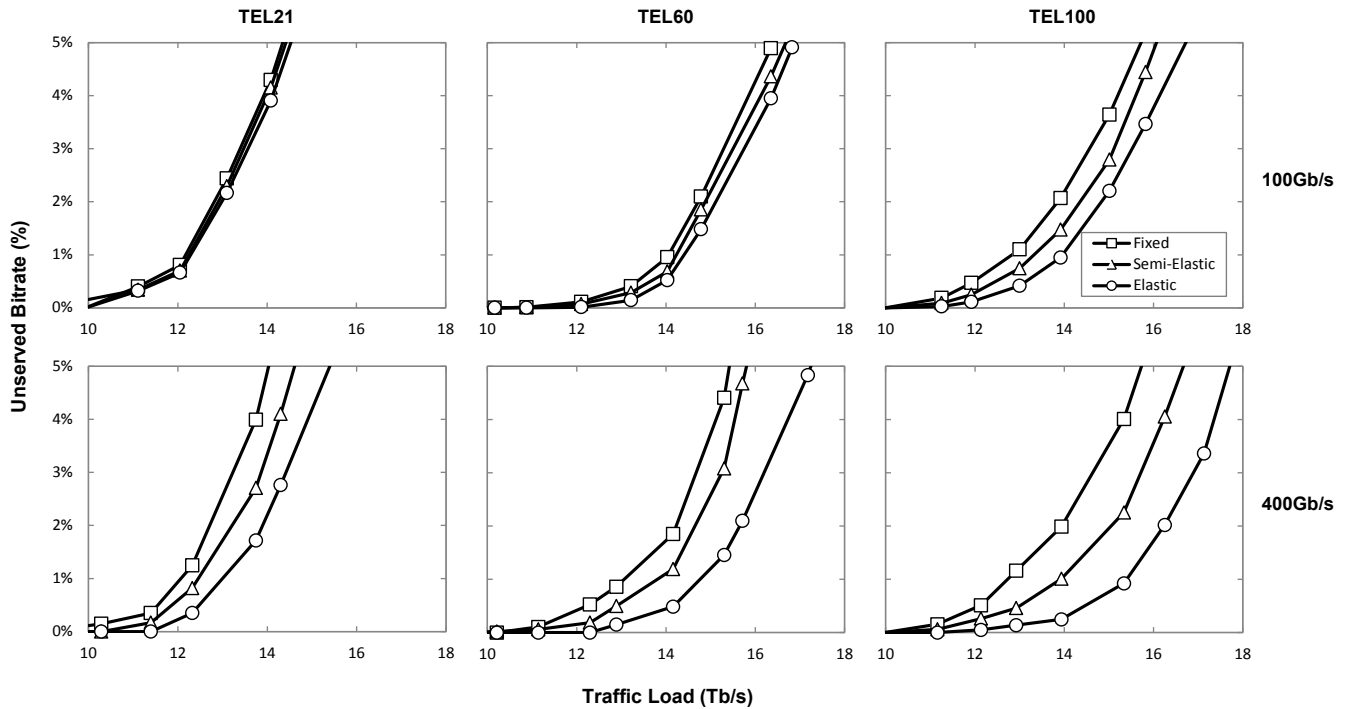


Fig. 4. Percentage of un-served bitrate against the traffic load for TEL21 (left), TEL60 (centre) and TEL100 (right) networks when the capacity of the lightpaths is limited to 100Gb/s (top) and 400Gb/s (bottom).

TABLE IV GAIN OF ADAPTIVE SA POLICIES VS. FIXED SA AT 1% OF UN-SERVED BIT RATE

Max. Capacity	SA Policy	TEL21	TEL60	TEL100
400 Gb/s	Elastic	7.73%	12.99%	20.99%
	Semi-Elastic	3.25%	5.67%	9.34%
100 Gb/s	Elastic	0.92%	2.47%	8.83%
	Semi-Elastic	0.60%	1.24%	3.85%

and the lightpath capacity is low, a large number of lightpath connections are established between each pair of aggregation networks and a relatively large fraction of these lightpath is always saturated. Hence, elasticity is not required in that scenario. Having the aggregation level gradually increased in TEL60 and TEL100, the benefits of elasticity also increase, however, they are still rather limited.

In contrast, the benefits from elasticity clearly appear when the lightpath capacity limit is increased to 400Gb/s. Although the performance gain is small for the network with high aggregation level (TEL21), the un-served bit-rate remarkably improves (decreases) for networks with lower aggregation levels (i.e., TEL60 and, especially, TEL100) if elastic SA policies are applied.

Regarding the SA policies, in all the analyzed scenarios the *Elastic* SA policy outperforms the *Semi-Elastic* SA policy which, on the other hand, performs better than *Fixed* SA.

In Table IV, we report the performance gain of elastic SA policies with respect to fixed SA. The results are obtained for the network load for which 1% of offered bit-rate is un-served. We can see that *Elastic* SA allows serving up to 21% of traffic more than *Fixed* SA in the TEL100 scenario with 400 Gb/s

lightpath capacity limit. In the same scenario, the gain of using the *Semi-Elastic* SA policy is just about 9%.

### C. Study of lightpath variability

Eventually, we investigate the relationship between the traffic aggregation level and the variability of each lightpath along the lime. To this end, the set of operating lightpaths is divided into three subsets, named L1, L2, and L3, depending on the degree of bit-rate variations in time:

TABLE V DISTRIBUTION OF LIGHTPATHS ACCORDING TO THE LEVEL OF VARIABILITY

Max. Capacity	Lightpath type	TEL21	TEL60	TEL100
100 Gb/s	L1	19.0%	15.2%	14.3%
	L2	34.9%	41.3%	42.9%
	L3	46.2%	43.5%	42.9%
400 Gb/s	L1	0.0%	0.0%	0.0%
	L2	94.8%	98.0%	100.0%
	L3	5.2%	2.0%	0.0%

- L1 contains all those lightpaths for which bit-rate variations are almost unappreciable, and consequently, the amount of allocated spectrum resources does not change in time. This is mainly the case of fully-loaded lightpaths which groom several demands and where statistical multiplexing keeps constant the total bit-rate at maximum.
- L2 includes lightpaths for which bit-rate variations are intensive within some range of minimum and maximum values. While aggregated traffic can reach the maximum bit-rate at a certain time, a minimum amount of traffic is always present.

- L3 contains those lightpaths for which the highest relative bit-rate fluctuations are observed with instantaneous changes from not being used to a peak where several spectrum slices are required.

In Table V, the distribution of lightpaths belonging to each of the above defined subsets is presented. These results are consistent with the discussion carried out in the analysis of the efficiency of SA policies in Sec. III.B and similar arguments can be used.

Firstly, there is a higher percentage of lightpaths of type L1 in the scenario with low lightpath capacity limit (100 Gb/s) compared to the scenario where 400 Gb/s lightpaths are allowed. This fact considerably reduces the amount of lightpaths making use of elasticity, and thus the performance of the fixed SA policy is close to elastic SA policies. That percentage decreases if the aggregation level is decreased (see TEL100 vs. TEL21).

Secondly, when 400 Gb/s lightpaths can be used, almost all lightpaths belong to set L2 and only a small fraction of lightpath is in set L3. Hence, lightpath capacity is always subject to changes, there are no saturated lightpaths, and only some lightpaths experience high capacity variations. On the other hand, the traffic fluctuations of lightpaths when the limit of 100 Gb/s is applied are much higher (see the percentage of lightpaths in set L3); especially, in the TEL100 scenario in which traffic aggregation is low and traffic variability is higher.

#### IV. CONCLUSIONS

In this paper, we have focused on dynamic adaptation of lightpath connections, by means of elastic spectrum allocation, in a flexgrid-based elastic optical network with time-varying traffic demands. We have addressed a scenario in which an EON core network connects a number of IP/MPLS metro area networks performing traffic aggregation. As we have found in our previous works, a large core network connecting a large set of small aggregation networks is a cost-effective solution. However, if the core network is extended towards the edges and the number of aggregation networks is increased then the level of traffic aggregation is decreased and the variability of traffic to be carried over the core network is higher.

To deal with that variability, in this paper we have proposed to make use of elastic spectrum allocation, which translates to the adaptation of spectrum allocated to lightpath connection in response to changes in traffic demands. We have analyzed two spectrum allocation policies, namely, a symmetric SA policy (referred to as *Semi-Elastic SA*) and an asymmetric SA policy (referred to as *Elastic SA*), and compared their performance vs. a *Fixed SA* policy, which does not allow for spectrum changes. For each elastic SA policy, we have developed a dedicated lightpath adaptation algorithm. The evaluation has been performed in a simulation environment assuming different network scenarios, which are characterized by different levels of traffic aggregation and lightpath capacity limits. We have shown that the effectiveness of lightpath adaptation in dealing with time-varying traffic highly depends

on both the aggregation level and the maximum lightpath capacity. In a network with low traffic aggregation, the best performance gap of about 21% (vs. the *Fixed SA* policy) is achieved for *Elastic SA* operating with high lightpath capacity limits.

It was shown that when core networks are extended towards the edges, the capacity of the lightpaths could be limited to deal with longer distances. In such scenarios, the effectiveness of elasticity is rather small. Therefore, as a final remark, those networks where the majority of lightpaths are some few hundred kilometers long (e.g. national European core networks) can currently take advantage of elasticity. On the opposite, additional research to extend the reach of 400 Gb/s (or even higher) lightpaths is needed so as to larger core networks could benefit also from elasticity.

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